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Reaching high-yield fusion with a slow plasma liner compressing a magnetized target

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Abstract

Dynamics of the compression of a magnetized plasma target by a heavy liner made of partially ionized high-Z material is discussed. A “soft-landing” (shockless) mode of the liner deceleration is analyzed. Conclusion is drawn that such mode is possible for the liners whose thickness at the time of the first contact with the target is smaller than, roughly, 10% of the initial (un-compressed) target radius. A combination of the plasma liner with one or two glide cones allows for a direct access to the area near the center of the reactor chamber. One can then generate plasma target inside the plasma liner at the optimum time. The other advantage of the glide cones is that they can be used to deliver additional fuel to the center of the target near the point of a maximum compression and thereby increase the fusion yield.

1. Introduction

In this paper we discuss some aspects of fusion systems spanning the range of densities between the Magnetic Confinement Fusion and Inertial Confinement Fusion. More specifically, we have in mind densities between 10^{18} cm^{-3} and 10^{22} cm^{-3} . An important ingredient in the plasma confinement in these systems is the presence of a strong-enough magnetic field that suppresses plasma heat conduction. This version of fusion is commonly called “Magnetized Target Fusion” (MTF) (See, e.g., Refs. [1,2] and references therein) or “Magneto-Inertial Fusion” (MIF) (e.g., [3]). Within this broad category of fusion systems, there exist many specific realizations. We concentrate on the version of a 3D adiabatic compression of a pre-formed magnetized target, as discussed in Ref. [1].

Fusion reactors based on this concepts will be pulsed devices, with the energy release per pulse in the range 100 MJ to 1 GJ. Accordingly, they have to address a stand-off issue for the permanent power supply system: the power supply should be situated outside the reaction chamber and, at the same time, allow for a rep-rate operation. An elegant solution to this problem is the use of plasma liners, generated by an array of ~ 100 plasma guns mounted at the periphery of the reaction chamber [4-6]. A simpler version of this system could be based on the acceleration of a heavy shell made of a high-A (A =atomic weight) material (a slow, high-A plasma liner) by thermal hydrogen plasma [7]. The liner is supposed to be generated near the walls of a chamber, 5-6 m in diameter, and accelerated towards the center by the pressure of a hydrogen plasma with a

temperature of a few electron-volts. Details of this process have been discussed in Ref. [7].

In this paper, we concentrate on the interaction of the liner with a quasi-spherical MTF (MIF) target, starting from the instant of the first liner-target contact and following the system until the stagnation and early stage of the rebound. In Sec. 2, we present scaling laws for a 3D self-similar adiabatic compression of the magnetized target by the liner. In Sec. 3, the role of the magnetic field in alpha particle confinement is discussed. Sec. 4 deals with a possibility of reaching a high hydrodynamic efficiency of the target compression by providing conditions for essentially shock-less interaction of the heavy liner with a target. In Sec. 5, a brief discussion of possible ways for creating a plasma target inside the slowly imploding liner is presented. Sec. 6 addresses an issue of possible increase of the fusion yield by injecting additional fuel into the hot plasma core, very much as it is done in Magnetic Confinement Fusion. Finally, Sec. 7 contains discussion of our main results.

We do not pretend that have found a final solution for MTF reactor: just identified some potentially promising leads for the further studies.

2. Scaling laws for a slow adiabatic compression of a plasma target

Consider a heavy plasma liner that adiabatically compresses a spherical magnetized target. We start with a spherical target of a radius r_0 . The liner thickness is assumed to be much less than the target radius – otherwise, the compression is inefficient (see below). We assume that the target is adiabatically compressed by the pdV work performed by the liner. The liner, as a result, is decelerated. This (admittedly simplistic) model allows us to get some insights into relative importance of various processes. We later add more complexity (and realism) to the model.

As we will see, the liner velocity is much less than the sound speed in the DT target. At the same time, the heat losses from the target (both radiation and heat conduction) are assumed to be small. Under such circumstances, the plasma compression can be considered as an adiabatic process. The plasma liner is made of a shell of a heavy, partially-ionized gas accelerated to the desired velocity by the pressure of a thermal, relatively cold (5-10 eV) hydrogen plasma [7].

Assuming that the initial beta was ~ 1 , one can show that, in a 3D implosion, the beta soon becomes higher than one (see Ref. [1]). Then, the contribution of the plasma to the pressure and energy density in the target would be much larger than respective contribution of the magnetic field. This is a favorable feature: most of the compressional work will go into the plasma, not into magnetic field, as it would be in the low-beta systems.

For the fully ionized plasma, one has

$$p = p_0 \left(\frac{r_0}{r} \right)^5; \quad T = T_0 \left(\frac{r_0}{r} \right)^2, \quad (1)$$

where p , T , and r are the target pressure, temperature, and radius; the subscript “0” corresponds to initial parameters of the target. The ratio of the initial r_0 to final r_f target radius is called “convergence,”

$$\frac{r_0}{r_f} \equiv C. \quad (2)$$

If we start from the temperature of 100 eV, the required radial convergence C for reaching the fusion temperature of 10 keV is ~ 10 .

The deceleration g of the liner is, obviously,

$$g = \frac{4\pi r^2 p}{m_L} = \frac{4\pi r_0^2 p_0}{m_L} \left(\frac{r_0}{r} \right)^3, \quad (3)$$

where m_L is the liner mass. This is an instantaneous deceleration for a particular value r of the radius. The highest acceleration is obviously reached near the stagnation point, when $r=r_f$. We denote this acceleration as g_f :

$$g_f = \frac{4\pi r_f^2 p_f}{m_L}. \quad (4)$$

One, obviously, has:

$$g = g_f \left(\frac{r_f}{r} \right)^3. \quad (5)$$

At the stagnation point, the liner energy is completely converted into the plasma energy. One has, therefore:

$$\frac{3}{2} p_f \left(\frac{4\pi r_f^3}{3} \right) = W_{L0} \equiv \frac{m_L v_{L0}^2}{2}, \quad (6)$$

where W_{L0} is the initial liner energy, and v_{L0} is the initial liner velocity. Of course, in reality there are intrinsic inefficiencies in this process, and we will discuss them later. From Eqs. (4)-(6) one finds:

$$g = \frac{v_{L0}^2}{r_f} \left(\frac{r_f}{r} \right)^3. \quad (7)$$

The energy conservation law shows that the liner velocity varies as

$$v_L = v_{L0} \frac{\sqrt{1 - (r_f/r)^2}}{\sqrt{1 - (r_f/r_0)^2}}. \quad (8)$$

Note that significant decrease of the liner velocity begins only at the radii that are 4-5 times less than the initial radius; 75% of the energy deposition occurs when the radius changes from $2r_f$ to r_f . One can easily show that the time t_f for the target to be compressed from r_0 to r_f is:

$$t_f = \frac{r_0}{v_{L0}} \left(1 - \frac{1}{C^2} \right) \approx \frac{r_0}{v_{L0}} \quad (9)$$

This discussion is illustrated by Fig. 1, where time-histories of r , v , and g are shown.

In our case, the “confinement time”, i.e., the time during which fusion reactions occur at a significant rate, can be identified as the time within which the target volume is near its minimum, between r_f and $r_f(1+\varepsilon)$. We assume that $\varepsilon=0.3$. The confinement time (the dwell time) is then

$$\tau \approx 2 \left(\frac{\varepsilon m_L}{2\pi r_f p_f} \right)^{1/2}. \quad (10)$$

We neglect here the fact that the target plasma may be additionally heated by alpha particles. This effect will not lead to a dramatic change of the results if the fusion gain Q is modest, $Q < 5-10$, which is characteristic of the batch-burn systems. Using the Lawson equation for the equicomponent mixture of DT, one then obtains:

$$Q = K n_f \tau, \quad (11)$$

where K is the Lawson coefficient, approximately $10^{-14} \text{ cm}^3 \text{ s}^{-1}$.

Using Eq. (6), one can express the dwell time (10) as

$$\tau \approx 2 \left(\frac{\varepsilon m_L r_f^2}{W_{L0}} \right)^{1/2}. \quad (12)$$

If we choose some specific values for the parameters r_f and n_f , we thereby fix the initial liner energy W_{L0} ($W_{L0} = 2\pi r_f^3 n_f T_f$, with $T_f=10 \text{ keV}$). The dwell time (12) scales then as $m_L^{1/2}$. In other words, it seems (see Eq. (12)) that the best fusion gain can be reached for as high liner mass as possible. However, this is incorrect: at a slow implosion velocity, which would correspond to a high mass (at a given energy), the target would actually never reach the ignition temperature, due to radiation losses. Obviously, in order for the target plasma to heat up during the implosion phase, one has to compress it rapidly enough.

In a lumped-parameter model of Ref. [8] that we follow here (see also Ref. [9]), a scan over dwell times (i.e., the liner masses) was made. The optimum turned out to correspond to $Q \sim 10$. This is the highest fusion gain that can be reached in the batch-burn model with an adiabatic compression of the target. More detailed calculations should include spatial distribution of parameters inside the target, as discussed by P. Parks (see reference to his analysis in Sec.4, p. 958 of paper [10]).

A factor that can additionally decrease the gain, is anomalous, Bohm-like transport. However, in the regimes of high collisionality characteristic of the MTF/MIF plasmas, the coefficient of the anomalous diffusion is always smaller than the Bohm coefficient (see [10,11]),

$$D < D_{Bohm}, \quad D_{Bohm}(cm^2/s) \approx \frac{6 \times 10^5 T(keV)}{B(T)} \quad (13)$$

With that, the diffusive heat loss does not significantly degrade performance of MTF targets. We will return to this issue in the next section.

Based on these simple estimates, one can expect that the “sweet spot” for adiabatically compressed targets lies in the domain determined by Eq. (11) and Eq. (12) with $Q=10$. The other constraints on the system parameters stem from relations (1), (2) and (6):

$$C = \left(\frac{T_f}{T_0} \right)^{1/2}; \quad (14)$$

$$n_0 = \frac{W_{L0}}{4\pi r_0^3 T_f}; \quad (15)$$

$$n_f = \frac{W_{L0} C^3}{4\pi r_0^3 T_f} = \frac{W_{L0} T_f^{1/2}}{4\pi r_0^3 T_0^{3/2}}; \quad (16)$$

$$m_L = \left(\frac{2\pi Q}{K} \right)^2 \frac{r_0^4 T_0^2}{\epsilon W_{L0}}. \quad (17)$$

Input parameters in this set of equations are the final and initial temperatures, T_f and T_0 , initial radius r_0 and the liner energy W_{L0} . One can set $T_f=10$ keV, and $T_0=0.1$ keV. We assume also that $\epsilon=0.3$, and take a maximum possible value for Q , $Q=10$. With that, we obtain the following characteristic equations (in “practical” units):

$$C=10; \quad (18)$$

$$n_0(cm^{-3}) = 5 \times 10^{19} \frac{W_{L0}(MJ)}{[r_0(cm)]^3}; \quad (19)$$

$$n_f(cm^{-3}) = 5 \times 10^{22} \frac{W_{L0}(MJ)}{[r_0(cm)]^3}; \quad (20)$$

$$m(g) = 0.35 \frac{[r_0(cm)]^4}{W_{L0}(MJ)}; \quad (21)$$

$$\tau(ns) = 10 \frac{[r_0(cm)]^3}{W_{L0}(MJ)}. \quad (22)$$

The liner velocity at the time when it first comes into contact with the target is:

$$v_{L0}(km/s) = 80 \frac{W_{L0}(MJ)}{[r_0(cm)]^2}. \quad (23)$$

These results are illustrated in Fig. 2.

The sound speed in the initial, 100 eV DT plasma is 130 km/s. For all reasonable choices of the system parameters, it is significantly higher than the initial liner velocity (for $r_0=10$ cm and $W_{L0} = 10$ MJ, $v_{L0}=8$ km/s). Later in the pulse, the sound speed in the target increases, whereas the liner velocity decreases. Therefore, the plasma compression can be considered adiabatic throughout the whole pulse. Of course, we assume that the energy losses from the target, be it radiation or thermal conduction, are small compared to the pdV work.

Although we have discussed implosions of spherical targets, all the scaling laws hold for 3-dimensional self-similar implosions of non-spherical targets, in particular, self-similar implosions of FRCs [1, 12]. We ignore here the dependence on the elongation parameter (the ratio of the target length to its radius). If needed, this dependence can be easily incorporated into our scalings.

3. Effects related to the magnetic field

The magnetic field in the initial state can be expressed in terms of plasma pressure and the parameter β (the ratio of the plasma pressure to the magnetic pressure). Making the same as before assumption about the initial plasma temperature (0.1 keV), one finds that

$$B_0(T) \approx 10^{-8} \sqrt{\frac{n_0(cm^{-3})}{\beta_0}}, \quad (24)$$

or, using Eq. (19),

$$B_0(T) \approx 70 \sqrt{\frac{W_{L0}(MJ)}{\beta_0[r_0(cm)]^3}}, \quad (25)$$

where the subscript “0” refers to the initial state. The magnetic field strength scales as $(r_0/r)^2$, see Ref. [1]. Therefore,

$$B_f(T) \approx 7000 \sqrt{\frac{W_{L0}(MJ)}{\beta_0[r_0(cm)]^3}} \quad (26)$$

The plasma beta in the final state will be

$$\beta_f = 10\beta_0. \quad (27)$$

In order the plasma energy in the final state to exceed the magnetic energy, a condition of $\beta_f > 2/3$ should hold, or $\beta_0 > 0.07$. We have assumed in Sec. 1 that, in the initial state, $\beta_0 \sim 1$, i.e., the plasma thermal energy exceeds the magnetic energy from the very beginning. However, our results will remain essentially unchanged even for smaller values of the initial beta, because the plasma energy would become greater than magnetic energy early in the implosion process. Still, for the further estimates we assume that $\beta_0 \sim 1$ (as in FRCs).

The magnetic field in the final state determines, among other things, the alpha-particle confinement. The figure of merit in this context is the ratio of 2.5 MeV alpha-particle gyroradius ρ_α to the final target radius r_f . One has from Eqs. (2), (18), and (26), with $\beta_0 \sim 1$,

$$\frac{\rho_\alpha}{r_f} \approx 3 \times 10^{-2} \sqrt{\frac{r_0(cm)}{W_{L0}(MJ)}} \quad (28)$$

For all cases of interest, this ratio is well below 0.1, signifying that a substantial fraction of alpha-particle energy will be deposited to the target (Fig. 1b).

For this last statement to be correct, one has also to check that the alphas slowing-down time τ_α is substantially shorter than the dwell time (12). One has [13, 14]:

$$\tau_\alpha(ns) \approx 10^{21} \frac{[T_f(keV)]^{3/2}}{n_f(cm^{-3})} \quad (29)$$

(we assumed that the Coulomb logarithm is equal to 10). Substituting $T_f = 10$ keV and using Eqs. (20) and (22), one finds:

$$\frac{\tau_\alpha}{\tau} \approx 3 \times 10^{-2}. \quad (30)$$

In other words, the energy transfer from the alphas to the bulk plasma occurs essentially instantaneously.

In the version of MTF that we discuss here, there is no issue of the alpha-particle energy deposition in the sense discussed, e.g., in Ref. [15]. In our case, alphas are magnetically confined and certainly have enough time to deposit all their energy to the bulk of the compressed plasma. Of course, we assume, that there exist closed drift surfaces in the plasma target. If this is not the case, as, in particular, in diffuse Z-pinchs, then alpha particle deposition becomes subject to the analysis of Ref. [15]. However, for the targets like FRC's, spheromaks and spherical tori that are the subject of our study, drift surfaces are closed

One can also note in passing that a build-up of a pressure of alpha particles in a reactors-tokamaks poses a serious problem, as the presence of fast particles causes a variety of instabilities [16]. This is due to the fact that reactors-tokamaks favor quite a

high plasma temperature, exceeding typically 30 keV near the magnetic axis [16]. Conversely, as was emphasized in Ref. [14], in the MTF environment the optimum plasma temperature is much smaller and, at any instant of time, the alpha particles are present only in very small numbers. So, they will not have a significant negative effect on the performance of MTF systems.

Now we return to the issue of the role of anomalous transport. As a characteristic scale time we take

$$\tau_{diff} \equiv \frac{r_f^2}{6D_{Bohm}}, \quad (31)$$

where the Bohm diffusion coefficient is defined by Eq. (13). Relating τ_{diff} to the dwell time (22) and using Eqs. (18), (26) with $\beta_0=1$, $T_f=10$ keV, we find:

$$\frac{\tau_{diff}}{\tau} = \frac{200[W_{0L}(MJ)]^{3/2}}{[r_0(cm)]^{5/2}}. \quad (32)$$

For the typical set of parameters, $W_{0L} \sim 10$ MJ, $r_0 \sim 10$ cm, this ratio is large (see Fig. 3).

4. “Soft landing” as a way of reaching high hydrodynamic efficiency of the adiabatic compression

As has been mentioned above, it is very hard (if possible at all) to reach Q above 10 in the adiabatic compression, batch-burn scheme. Therefore, in order to have any chance for this concept to become a basis for an energy-producing reactor, one has to assure that the efficiency of the hydrodynamic compression is high.

We argue that reaching a high efficiency is potentially possible by the use of an initially thin liner, with a thickness not exceeding ~ 0.1 of the initial target radius. We mean here not an initially solid, thin liner discussed, e.g., in Ref. [1], but a plasma liner. As we will show, under a relatively broad set of conditions, its interaction with the target would give rise to almost complete conversion of the initial liner kinetic energy to the target thermal energy. We, of course, imply, in agreement with Ref. [7], that the liner thermal energy is much less than its kinetic energy.

A concern is that, when such a liner slams into a target, shock waves cause conversion of a significant part of a liner energy into its thermal energy, leading to the liner broadening, and, eventually, to a significant decrease of the target compression efficiency. On the other hand, in our case, the liner starts compressing the target at the stage where target pressure and density are very low, and cannot cause any significant deceleration of the liner. The mode of the liner-target interaction in our case is a “soft landing” mode, where the liner starts decelerating very gently (Fig.1), with the deceleration g gradually increasing, but never causing a sudden stop of the liner-plasma interface. Eventually, of course, the interface stops and rebounds, but this happens in a gentle, adiabatic manner. A more quantitative description follows below.

In the frame co-moving with the liner, the scale-height h (liner thickness) is determined by the equation

$$\frac{dp_L}{dz} = -g\rho_L \quad (33)$$

The axis “ z ” is directed outward from the target-liner boundary. The subscript “ L ” refers to the liner parameters. For the polytropic liner of a constant temperature T_L , one has $p_L = p_{Lb}\rho_L/\rho_{Lb}$, where the subscript “ b ” designates the values of the liner parameters at the liner-plasma boundary. One obviously has $p_{Lb} = p$, where p is the pressure of the plasma target. Then Eq. (33) yields: $p_L/p_{Lb} = \rho/\rho_{Lb} = \exp(-z/h)$, where the scale-height h (the liner thickness) is:

$$h = \frac{p}{g\rho_{Lb}} \quad (34)$$

For a polytropic gas, the total internal energy of the liner is

$$E_L = \frac{4\pi r^2 h p}{\gamma - 1} \quad (35)$$

In order for the compression to be efficient, this energy must be much less than the internal energy of the target, which is $2\pi r^3 p$. Therefore, we conclude that, for the compression to be efficient, the condition

$$h << \frac{r(\gamma - 1)}{2} \quad (36)$$

must hold, at least near the stagnation point.

For the polytropic liner, the liner compression leads to an increase of the internal energy. Taking internal energy at some reference radius r to be $E_L(r)$, one finds that

$$E_{Lf} = E_L(r) \left(\frac{p_f}{p(r)} \right)^{\frac{\gamma-1}{\gamma}} \quad (37)$$

Given the scaling (1), one obtains:

$$E_{Lf} = E_L(r) \left(\frac{r}{r_f} \right)^{5\frac{\gamma-1}{\gamma}} \quad (38)$$

In the absence of the heat exchange between the liner and the external world, this would yield an estimate of the internal liner energy at stagnation. As we have already mentioned, it must be significantly less than the plasma energy at this point (approximately equal to the initial liner kinetic energy W_{L0}). This sets the limit on the liner internal energy at the radius at which the gravitational equilibrium has established.

As an example, take this radius to be $3r_f$, and $\gamma=1.4$. Then one finds from Eq. (38) that $E_{L,f}=4E_L(r=3r_f)$. For this example, to ensure a 80% efficiency of the target heating at the most important stage of the implosion process, one has to have $E_L(r=3r_f)$ less than 5% of the initial liner energy W_{L0} .

The liner will lose heat via radiation to the external world and acquire heat due to the energy losses from the plasma target. In our example, in order not to change our estimates of the liner parameters significantly, the plasma energy loss during the compression from $3r_f$ to r_f must be less than, roughly, 10% of the final target energy. This number seems to be reasonable: the target design must indeed be such as to make the energy loss from the target to be small. We leave for further work a more detailed analysis of the liner energy balance at the final stage of the implosion.

Now we check that the liner slowing down at this stage occurs indeed in the “gentle” manner. This means that the deceleration g that determines the equilibrium (31) changes smoothly, without sudden jolts that may lead to development of shocks and cause a strong non-adiabatic heating of the liner. The smoothness criterion is:

$$\frac{\dot{g}}{g} \ll \frac{s_L}{h}, \quad (39)$$

where s_L is a sound speed in the liner material. The left hand side can be evaluated from Eqs. (7) as:

$$\frac{\dot{g}}{g} = 3v_0 \frac{\sqrt{r^2 - r_f^2}}{r^2}. \quad (40)$$

The liner sound speed is

$$s_L = \sqrt{\gamma \frac{(\bar{Z} + 1)T_L}{Am_p}}. \quad (41)$$

By noting that the liner pressure at the interface is equal to the target pressure p , one has:

$$p = \frac{\bar{Z} + 1}{Am_p} T_L \rho_{Lb}. \quad (42)$$

After that, by substituting Eqs. (34), (40), (41), and (42) into Eq. (39), one obtains the following criterion:

$$T_L \ll \frac{Am_p v_0^2}{2} \times \frac{2\gamma}{9(\bar{Z} + 1)} \times \frac{r_f^4}{r^2(r^2 - r_f^2)}. \quad (43)$$

This criterion is satisfied (although by a modest margin) for the liner temperature below ~ 0.5 eV at the radii $r < 2.5r_f$, where main energy deposition takes place. Creating thin liners favors high atomic weight materials: as the liner temperature will be small (due to

radiation losses), the average charge state \bar{Z} will not exceed a few, so that the ratio $(\bar{Z}+1)/A$ would scale as $1/A$.

The previous discussion was related to the late phase of the implosion, from roughly $2.5r_f$ to r_f . Consider now an early phase, from the first contact of the inner surface of the liner with the target plasma, until the time where the liner compresses and reaches the hydrostatic equilibrium (33) in the effective gravitational field. The liner average velocity at this stage remains essentially constant and equal to v_0 , because the target energy remains still small compared to the liner initial energy (Eq. (8) and Fig.1). The target pressure is small and does not affect the liner dynamics in any significant way. The liner is just coasting towards the center and its thickness does not change significantly compared to its value just before the first contact between liner and plasma. This initial thickness should, of course, be significantly smaller than r_0 . The analysis presented in Ref. [7] shows that it is feasible (although not simple) for the liners made of high-atomic-weight materials with $A \sim 100-150$.

The summary of the results presented in this section is qualitatively illustrated by Fig. 4, where the relative thickness of the liner h/r is presented as a function of time for the time segment between the instant when the liner has just touched the surface of the target and stagnation at $t=t_f$. The time is measured from the instant of a first contact, where the liner thickness is assumed to be $0.1r_0$. Initially, the liner is coasting with a very small deceleration, and the thickness h does not decrease, so that the ratio h/r initially increases. However, at $t \sim 0.8t_f$ the deceleration begins to increase, and the liner begins to thin down according to Eq. (34), due to increasing g . So, the ratio h/r begins to decrease rapidly, reaching the value $\sim 0.1-0.2$ near the stagnation point. Detailed description of this pre-stagnation thinning would require quantitative analysis of the effects of excitation and ionization in the liner on the equation of state, which would bring us well beyond a scoping study presented in this paper.

5. Creating target inside the plasma liner

Creating initial magnetized target is a complex task. As we have seen, its initial energy should be equal to approximately 1% of the liner energy. For a 10 MJ liner this means that the target has to contain initially 100 kJ. In addition, initial magnetic field of ~ 100 kG has to be generated in the target. The target is basically a ball of a 100-eV plasma with embedded magnetic field. As we have seen, its sound speed is significantly higher than the implosion velocity of the heavy liner. The time between the heavy liner creation near the chamber walls and its first contact with the target plasma, for the chamber radius of 2-3 m, will be in the range of many hundreds of microseconds [7], whereas the time for the just created target to expand will be of the order of a few microseconds. So, if created too early, when the heavy liner is, say, half-way from the chamber walls, the target would rapidly expand and cool down. To avoid this difficulty, the target can be generated just at the time where the liner has already approached the desired initial target radius (~ 10 cm in our characteristic case). The target formation time would not exceed a few sound transit times over the target initial radius, so that the slowly moving liner would cover a fraction of the desired target radius during the target formation. All this points at the need to create the target inside the moving liner, at the time when the liner radius is not significantly greater than r_0 .

Leaving more creative ways of target generation for the future analyses, we consider here the most straightforward technique based on the use of two insertion (glide) cones, as schematically shown in Fig. 5. The use of the glide cones was envisaged in Ref. [17] as a way of generating spheromak target inside the liner (Fig. 6). The conical electrodes have been successfully used in current-driven implosions of spherical, initially solid liners [18]. Similar configuration is used in experiments on fast ignition (see Ref. [19] and references therein). In these experiments, as well as in the related computer simulations (see Ref. [19]), the feasibility of such arrangement has been established

The presence of the sacrificial insertion cones would allow accommodating the circuitry and the gas-puff system needed for the creation of a magnetized target plasma near the center of the device, without disrupting the heavy liner that has been launched well before that. We leave the clarification of specific details for the further work. Here we only mention that the cones can be made quite light; also, they will be needed only for the creation of the target, this meaning that the required energy will be at the level of 1% of the energy that will be later delivered by the plasma liner. This would, therefore, be an intermediate approach between a full detachment of the target from the external power source and its direct mechanical (and electrical) connection to the external power source, where the full energy would be delivered to the implosion system by disposable conductors, as in Refs. [20, 21].

6. Increasing the fusion yield by the fuel injection

It has been realized long time ago (e.g., [1]) that the maximum fusion gain that can be reached in batch-burn MTF systems can hardly exceed $Q \sim 10$. Such a gain is only marginally acceptable for the energy-producing system, and increasing Q by a factor of a few is highly desirable. An obvious approach to solving this problem is adding some fuel to the target where fusion temperature has already been reached, and the alpha-particle energy release became comparable to the compressional heating. Ref. [4] has mentioned the possibility of using a dense layer of DT at the inner surface of a fast plasma liner. This layer would be heated by alpha particles released in the target core. This approach is reminiscent of a propagating burn approach in ICF (e.g., [22]). In the context of plasma liners, it is still under investigation [3, 6].

Certainly, an approach discussed in our present paper, with its slow liner and good alpha particle confinement in the fusion core, is not suitable for the use in the propagating burn system. To increase the yield, we suggest to use a fuel injection *to the hot target core*, starting just before the point of the maximum compression and ending shortly thereafter. This possibility has been mentioned to one of the authors (D.R.) by E. Velikhov (1992) and G. Logan (1997). We believe that the setting of Fig. 5, 6 adds some degree of realism to this idea, as it provides the way of reaching the hot plasma core without interfering with the liner.

If $Q \sim 10$ state is reached, then the alphas start making significant contribution to the plasma heating: for $Q \sim 10$, amount of heat produced by alphas is twice as much as it was initially deposited to the plasma. By adding twice as much fuel as was available initially, one would avoid the (unwanted) overheating and, at the same time, increase the reaction rate by a factor of 9. This would, of course, lead to faster target expansion during the rebound. Still, increasing the fusion yield by a factor of 3-4 seems to be feasible. We

believe that getting now into more detail and optimizing of the injection time-history is somewhat premature, as one has first to identify the way of injecting fuel into the hot plasma core.

Adding large amounts of the fuel to the plasma core was considered by D. Barnes [23], without specifying the delivery mechanism. It was concluded in Ref. [23] that fuel influx through the whole plasma surface may allow reaching extremely high gains. We leave analysis of this intriguing idea in the setting of Fig. 5 for the future work.

Conceptually, adding a modest amount of fuel to the hot plasma reminds the fuel injection into tokamaks, including ITER [24]; in this regard, we are going to exploit the features of MTF systems that make them similar to their MFE counterparts. Among possible ways of core fuel injection for tokamaks are pellet injection and compact toroid injection [24]. However, in our case, despite much smaller dimensions of the plasma, the line density is much higher. Still, both of the aforementioned approaches may hold some promise. In our case, one can also use injection of a narrow jet of fuel. The jet velocity has to be smaller than the plasma sound speed, since otherwise the creation of the jet would require more energy than was spent on the initial plasma implosion. The plasma beta in the final state is quite high, and the jet wouldn't have to struggle with the penetration through the high magnetic field. It may be necessary to generate jets with some magnetic field inside them, that would prevent the jet material from mixing with the peripheral plasma in the target. The particle inventory, as has already been mentioned, should be about twice the hot plasma inventory.

Characteristic duration of the fuelling process should be comparable with the dwell time, which is in the range of 10^{-6} s for the target of the final radius of 1 cm and energy of 10 MJ.

Plasma jets for refueling can be generated by special sources situated near the tips of the cones. The other possibility is a creative use of the jetting phenomena in the interaction of the plasma liner with the outer surface of the cone, where a small amount of the fuel could be stored near the tip of the cone and released at the appropriate time.

7. Discussion

We have discussed several modifications of MTF systems driven by the heavy plasma liner [7]. The first one is related to an attempt to increase the hydrodynamic efficiency of the adiabatic compression by operating the system in a shock-less, “soft landing” mode. Reaching this mode imposes rather strict constraints on the liner thickness, just prior to its first contact with the plasma target. The liner thickness at this time should not exceed 0.1 of target radius. The liner should also be relatively cold, with the temperature of a fraction of electron-volt. Radiative heat losses from the liner at the stage of its acceleration towards the target should help in satisfying this condition (see [7]).

The second modification consists in the use of the insertion cones to generate the target plasma. This approach will probably work, as it has been successfully used in the geometrically similar systems [18, 19] (although in a very different parameter domain).

Finally, we suggest to use a fuel injection technique similar to the one used in MFE systems, to increase amount of fuel near the point of the maximum compression by a factor of 2-3. This technique could lead to an increase of the fusion yield by a factor of

3-4 (i.e., to 30-40) and make the system more energy efficient than a batch-burn system considered in [1].

There remain a number of physics and technology issues that we haven't touched upon in this paper. The most prominent physics issue is that of the liner stability. It should be studied both numerically and analytically for the conditions characteristic of MTF implosions, which are quite unique in many respects.

The most difficult engineering issue is that of the compatibility of the plasma liner approach with the need to breed tritium and protect the walls of the reaction chamber. Here one has to analyze the compatibility of using thick liquid blanket with the overall "architecture" of the system.

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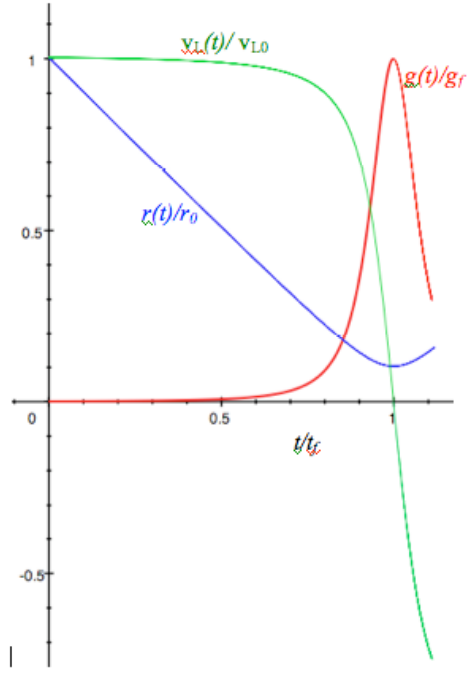


Fig. 1. Time-histories of the liner radius (coinciding with the outer radius of the target), blue curve, liner velocity (green curve), and liner deceleration (red curve). The normalization factors g_f and t_f are defined by Eqs. (4) and (9), respectively. Note a long period during which the liner is coasting with essentially constant velocity.

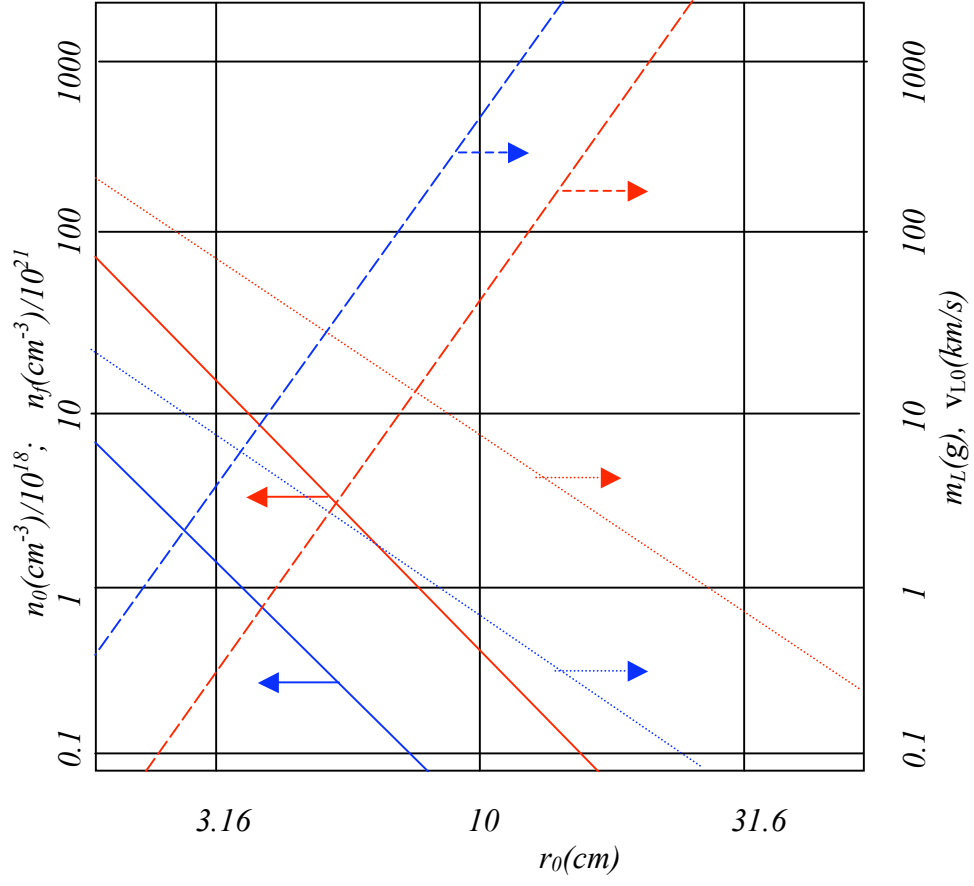


Fig. 2. Scalings for quasi-spherical implosions. Red lines: input energy 10 MJ; blue lines: input energy 1 MJ. Solid lines: plasma density; dashed lines – liner mass; dotted lines: liner velocity.

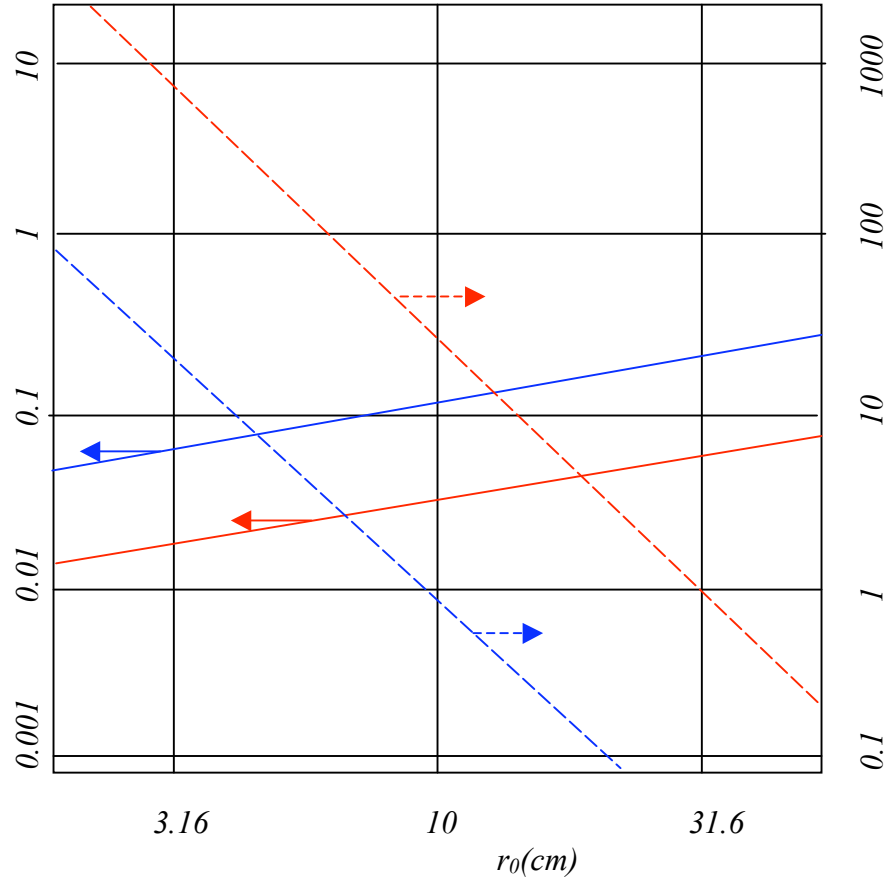


Fig. 3. Additional scalings for spherical implosions. Red lines: 10 MJ, blue lines: 1 MJ; solid lines: parameter ρ_α/r_f , Eq. (28); dashed lines: τ_D/τ , Eq. (32). Note different scales on the left and the right vertical axes.

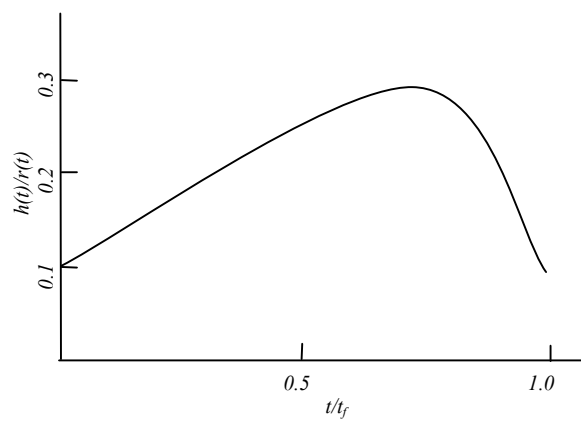


Fig. 4. A sketch of the time history of the relative liner thickness.

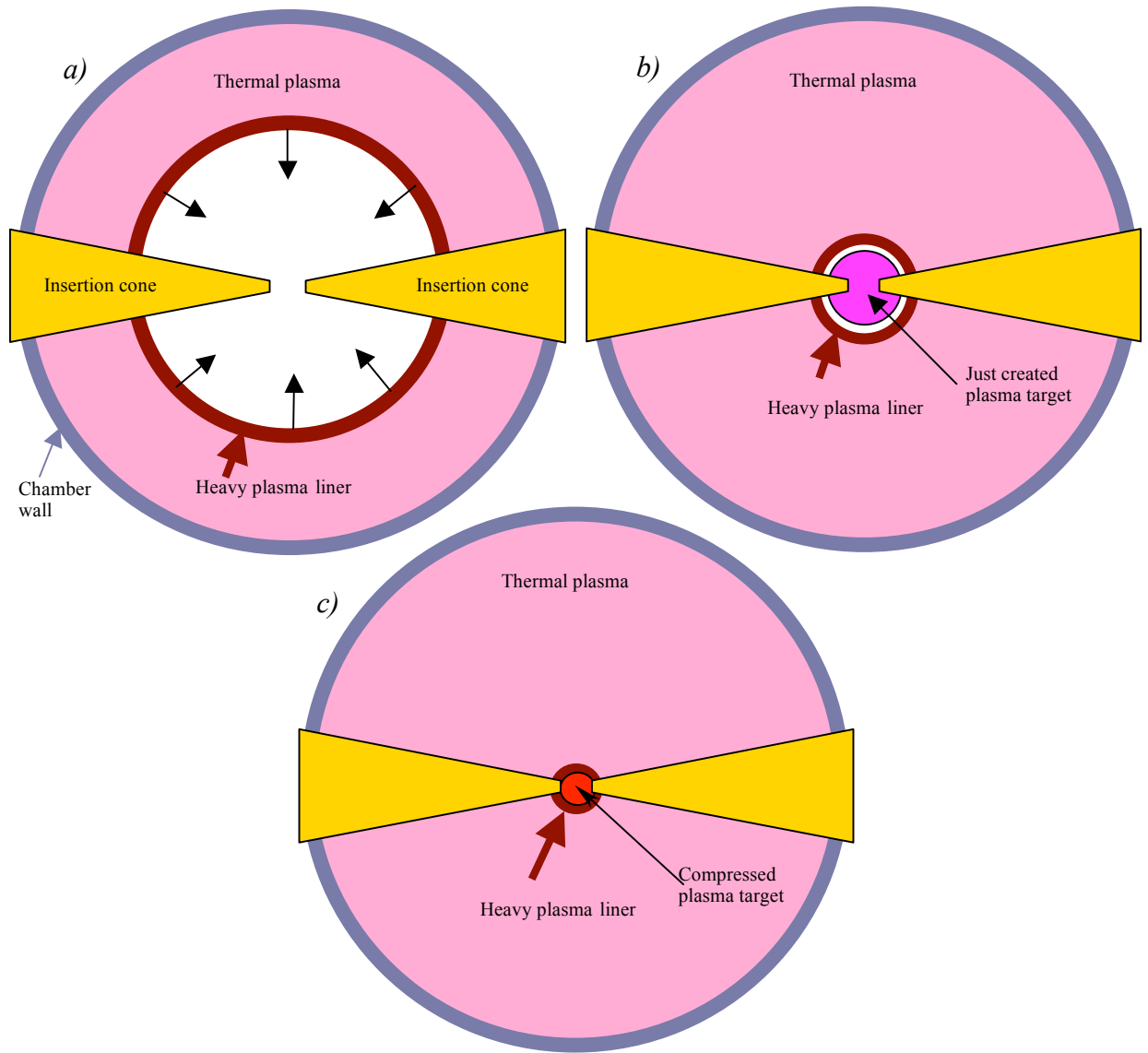


Fig. 5 Schematic of a plasma liner gliding over the surfaces of two insertion cones, not to scale. Chamber radius is 2-3 m, whereas the radius of the imploded target on panel c) is ~ 1 cm. Glide cones are inserted prior to the beginning of the shot. Panel a) corresponds to the first half of the liner acceleration process, roughly 200-300 μs after beginning of the shot. Panel b) corresponds to the point where target has just been created and the liner is about to start compressing it. Panel c) corresponds to the stagnation point.

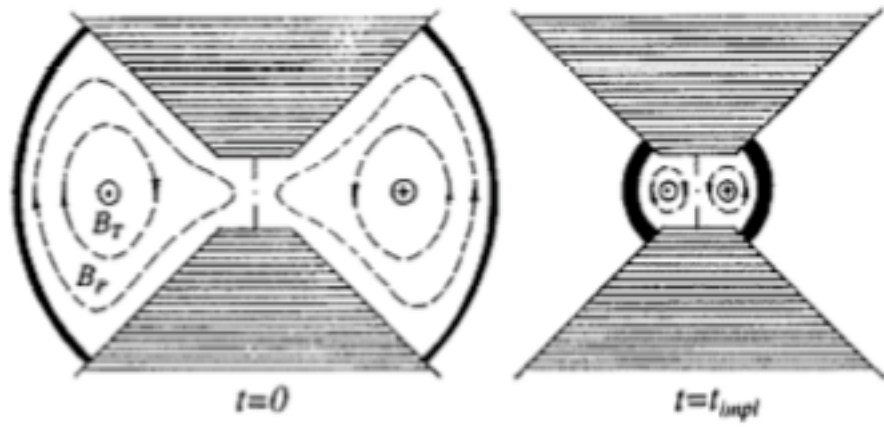


Fig. 6 Implosion of a quasi-spherical compact toroid by a liner gliding over the surface of two cones. Left panel – beginning of the implosion; right panel – near stagnation.